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(54) Title: POWER FACTOR CORRECTION DRIVE CIRCUIT TOPOLOGIES AND CONTROL FOR SWITCHED RELUCTANCE MACHINES

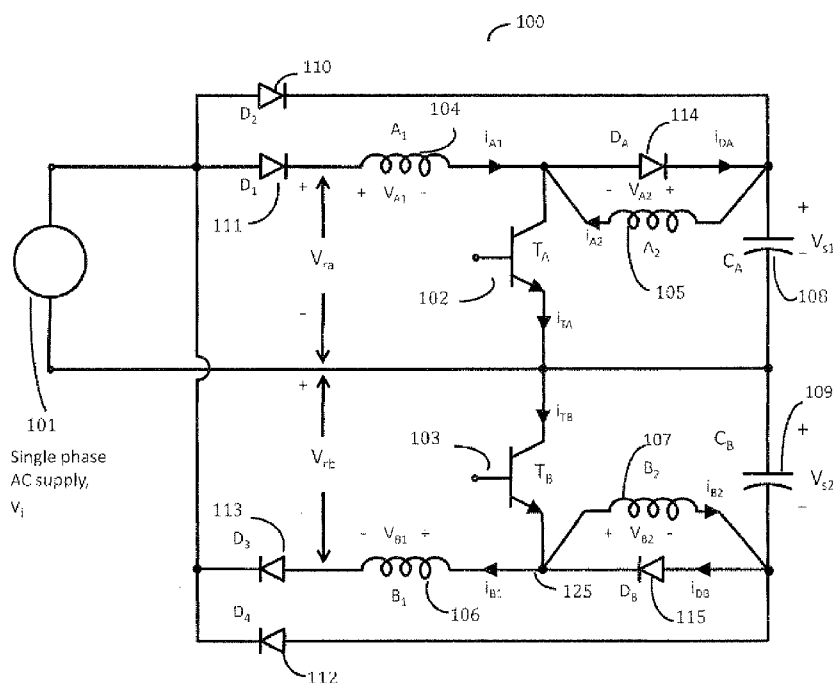


Fig. 1

(57) Abstract: Drive circuits that provide power factor correction and input current waveform shaping for controlling the speed and torque in a switched reluctance machine (SRM). The machine's phase windings are split into two segments, one of which is used for active power factor correction, input ac current waveform shaping and partial torque generation and the other of which is used for torque generation.



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AMENDED CLAIMS

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1. A power converter for supplying power to a motor, the power converter comprising for a motor phase:

no more than three diodes;

a single capacitor; and

a single switch that conducts current when activated and does not conduct current when deactivated, wherein:

the three diodes, capacitor, and switch are interconnected such that when interconnected with a single-phase alternating current supply and first and second series-connected windings of the motor phase:

a first operational mode of the power converter exists in which current is conducted from the single-phase alternating current supply through the single switch and the first and second motor phase windings,

energy is stored in the capacitor during the first operational mode by the conduction of current through one of the diodes to the capacitor, and

a second operational mode exists in which energy stored in the capacitor during the first operational mode is discharged by the conduction of current through the second motor phase winding and the switch, and

each of the first and second motor phase windings is within an independent current path between the single-phase alternating current supply and the single switch during the first operational mode.

2. A power converter for supplying power to a motor, the power converter comprising for two phases of the motor:

no more than three diodes;

a single capacitor; and

no more than two switches that each conducts current when activated and does not conduct current when deactivated, wherein:

the three diodes, capacitor, and two switches are interconnected such that when interconnected with a single-phase alternating current supply through a full-wave bridge rectifier, first and second series-connected phase windings of the motor for a first of the two motor phases, and third and fourth series-connected phase windings of the motor for a second of the two motor phases:

a first operational mode of the power converter exists in which current is conducted through a first of the two switches and the first and second motor phase windings,

a second operational mode of the power converter exists in which current is conducted through a second of the two switches and the third and fourth motor phase windings,

energy is stored in the capacitor during the first and second operational modes by the conduction of current through one of the diodes to the capacitor,

a third operational mode exists in which energy stored in the capacitor during the first or second operational modes is discharged by the conduction of current through the second motor phase winding and the first switch when no current is conducted through the first motor phase winding, and

a fourth operational mode exists in which energy stored in the capacitor during the first or second operational modes is discharged by the conduction of current through the fourth motor phase winding and the second switch when no current is being conducted through the third motor phase winding.

3. A power converter for supplying power to a motor, the power converter comprising for a phase of the motor:

no more than two diodes;

a single capacitor; and

no more than two switches that each conducts current when activated and does not conduct current when deactivated, wherein:

the two diodes, capacitor, and two switches are interconnected such that when interconnected with a single-phase alternating current supply through a full-wave bridge rectifier and first and second series-connected windings for the motor phase:

a first operational mode of the power converter exists in which current is conducted through a first of the two switches and the first motor phase winding,

a second operational mode of the power converter exists in which current is not conducted through the first switch and energy is stored in the capacitor,

a third operational mode exists in which energy stored in the capacitor during the second operational mode is discharged by the conduction of current through both of the switches and the second motor phase winding.

4. A power converter for supplying power to a motor, the power converter comprising for two phases of the motor:

no more than four diodes;

a single capacitor; and

no more than four switches that each conducts current when activated and does not conduct current when deactivated, wherein:

the four diodes, capacitor, and four switches are interconnected such that when interconnected with a single-phase alternating current supply through a full-wave bridge rectifier, first and second series-connected windings of a first of the motor phases, and third and fourth series-connected windings of a second of the motor phases:

a first operational mode of the power converter exists in which current is conducted through a first of the four switches and the first motor phase winding, but no current flows through a second of the four switches,

a second operational mode of the power converter exists in which current is conducted through the second switch and the second motor phase winding, but no current is conducted through the first switch,

energy is stored in the capacitor during the first and second operational modes by: (1) the conduction of current through the first motor phase winding and a first of the four diodes to the capacitor or (2) the conduction of current through the second motor phase winding and a second of the four diodes to the capacitor,

a third operational mode exists in which energy stored in the capacitor during the first or second operational modes is discharged through the third motor phase winding when current is conducted through the first switch and a third of the four switches, and

a fourth operational mode exists in which energy stored in the capacitor during the first or second operational modes is discharged through the fourth motor phase winding when current is conducted through a fourth of the four switches and the second switch.

5. A power converter for supplying power to a motor, the power converter comprising for two phases of the motor:

no more than three diodes;

a single capacitor; and

no more than three switches that each conducts current when activated and does not conduct current when deactivated, wherein:

the three diodes, capacitor, and three switches are interconnected such that when interconnected with a single-phase alternating current supply through a full-wave bridge rectifier, first and second series-connected windings for a first of the two motor phases, and third and fourth series-connected phase windings for a second of the two motor phases:

a first operational mode of the power converter exists in which current is conducted through a first of the three switches and the first motor phase winding, but no current is conducted through a second of the three switches,

a second operational mode of the power converter exists in which current is conducted through the second switch and the second motor phase winding, but no current is conducted through the first switch,

energy is stored in the capacitor during the first and second operational modes by: (1) the conduction of current through the first motor phase winding and a first of the three diodes to the capacitor or (2) the conduction of current through the second motor phase winding and a second of the three diodes to the capacitor,

a third operational mode exists in which energy stored in the capacitor during the first or second operational modes is discharged by the conduction of current through the third motor phase winding, the first switch, and a third of the three switches, and

a fourth operational mode exists in which energy stored in the capacitor during the first or second operational modes is discharged by the conduction of current through the fourth motor phase winding and the second and third switches.

6. A power converter for supplying power to a motor, the power converter comprising for a phase of the motor:

a single diode;

a single capacitor; and

a single switch that conducts current when activated and does not conduct current when deactivated, wherein:

the diode, capacitor, and switch are interconnected such that when interconnected with a single-phase alternating current supply through a full-wave bridge rectifier and first and second windings for the motor phase:

a first operational mode of the power converter exists in which current is conducted through the switch and the first motor phase winding,

a second operational mode of the power converter exists in which energy stored in the first motor phase winding is discharged, by the conduction of current through the first motor phase winding and the diode to the capacitor, to be stored as energy in the capacitor, and

a third operational mode exists in which energy stored in the capacitor during the second operational mode is discharged by the conduction of current through the second motor phase winding, and

the current conducted through the second motor phase winding during the third operational mode, for discharging the energy stored in the capacitor during the second operational mode, is not conducted through a switch.

7. A power converter for supplying power to first and second series-connected windings of a motor phase, the power converter comprising:

first, second, and third unidirectional current elements that each conducts current in only one direction between a current input terminal and a current output terminal;

a first capacitive element for storing energy across first and second terminals;

a first switch that conducts current between a current input terminal and a current output terminal when activated and does not conduct current between the current input and output terminals when deactivated, wherein:

the current input terminals of the first and second unidirectional current elements are directly connected by a first node,

the first terminal of the first capacitive element is directly connected to the current output terminals of the first and third unidirectional current elements by a second node,

the current input terminal of the third unidirectional current element is directly connected to the current input terminal of the first switch by a third node,

the second terminal of the first capacitive element is directly connected to the current output terminal of the first switch by a fourth node,

when: (1) a single-phase alternating current supply has one terminal directly connected to the first node and has another terminal directly connected to the fourth node, (2) the first motor phase winding has a first terminal directly connected to the current output terminal of the first unidirectional current element and a second terminal directly connected to the third node, (3) the second motor phase winding has a first terminal directly connected to the second node and a second terminal directly connected to the third node, and (4) the first switch is activated, then

a first operational mode exists in which current is conducted through the first switch and the first and second motor phase windings while a positive voltage, with respect to the voltage applied to node 4, is applied to the current input terminals of the first and second unidirectional current elements,

energy is stored in the first capacitive element by the conduction of current through the first unidirectional current element to the capacitive element, during the first operational mode, and

a second operational mode exists in which energy stored in the first capacitive element during the first operational mode is discharged by the conduction of current through the second motor phase winding while a negative voltage, with respect to the voltage applied to the fourth node, is applied to the current input terminals of the first and second unidirectional current elements.

8. A power converter for supplying power to first and second series-connected windings of a first motor phase and third and fourth series-connected windings of a second motor phase, the power converter comprising:

first, second, third, and fourth unidirectional current elements that each conducts current in only one direction between a current input terminal and a current output terminal;

a capacitive element for storing energy across first and second terminals;

first and second switches that each conducts current between a current input terminal and a current output terminal when activated and does not conduct current between the current input and output terminals when deactivated, wherein:

the first terminal of the capacitive element and the current output terminals of the first, second, and third unidirectional current elements are directly connected by a first node,

the current input terminal of the second unidirectional current element is directly connected to the current input terminal of the first switch by a second node,

the second terminal of the capacitive element is directly connected to the current output terminals of the first and second switches by a third node,

the current input terminal of the third unidirectional current element is directly connected to the current input terminal of the second switch by a fourth node,

when: (1) a single-phase alternating current supply is connected to the power converter through a full-wave bridge rectifier such that a positive voltage terminal is directly connected to the current input terminal of the first unidirectional current element by a fifth node and has a negative voltage terminal directly connected to the third node, (2) the first motor winding has a first terminal directly connected to the fourth node and a second terminal directly connected to the second node, (3) the second motor winding has a first terminal directly connected to the second node and a second terminal directly connected to the first node, (4) the third motor winding has a first terminal directly connected to the fifth node and a second terminal directly connected to the fourth node, and (4) the fourth motor winding has a first terminal directly connected to the first node and a second terminal directly connected to the fourth node , then

a first operational mode exists in which current is conducted through the first and second motor windings, while the first switch is activated,

a second operational mode exists in which current is conducted through the third and fourth motor windings, while the second switch is activated,

energy is stored in the capacitive element during the first and second operational modes,

a third operational mode exists in which energy stored in the capacitive element is discharged by the conduction of current through the second motor winding and the first switch while no current is conducted by the first motor winding, and

a fourth operational mode exists in which energy stored in the capacitive element is discharged by the conduction of current through the fourth motor winding and the second switch while no current is conducted by the third motor winding.

9. A power converter for supplying power to first and second series-connected windings of a motor phase, the power converter comprising:

first and second unidirectional current elements that each conducts current in only one direction between a current input terminal and a current output terminal;

a capacitive element for storing energy across first and second terminals;

first and second switches that each conducts current between a current input terminal and a current output terminal when activated and does not conduct current between the current input and output terminals when deactivated, wherein:

the first terminal of the capacitive element, the current input terminal of the second switch, and the current output terminal of the first unidirectional current element are directly connected by a first node,

the current input terminal of the first unidirectional current element is directly connected to the current input terminal of the first switch by a second node,

the current output terminal of the second switch is directly connected to the current output terminal of the second unidirectional current element by a third node,

the second terminal of the capacitive element is directly connected to the current output terminal of the first switch and the current input terminal of the second unidirectional current element by a fourth node,

when: (1) a single-phase alternating current supply is interconnected with the power converter through a full-wave bridge rectifier whose negative voltage terminal is directly connected to the fourth node, (2) the first motor phase winding has a first terminal directly connected to the positive terminal of the full-wave bridge rectifier and a second terminal directly connected to the second node, and (3) the second motor phase winding has a first

terminal directly connected to the second node and a second terminal directly connected to the third node, then:

a first operational mode exists in which current is conducted through the first motor phase winding, while the first switch conducts is activated,

a second operational mode exists in which current is conducted through the first motor phase winding and the first unidirectional current element to charge the capacitive element, while the first switch is deactivated,

a third operational mode exists in which energy stored by the capacitive element during the second operational mode is discharged by the conduction of current through the second motor phase winding when both the first and second switches are activated.

10. A power converter for supplying power to first and second series-connected windings of a first motor phase and third and fourth series-connected windings of a second motor phase, the power converter comprising:

first, second, third, and fourth unidirectional current elements that each conducts current in only one direction between a current input terminal and a current output terminal;

a capacitive element for storing energy across first and second terminals;

first and second switches that each conducts current between a current input terminal and a current output terminal when activated and does not conduct current between the current input and output terminals when deactivated, wherein:

the first terminal of the capacitive element, the current output terminals of the first and third unidirectional current elements, and the current input terminals of the first and third switches are directly connected by a first node,

the second terminal of the capacitive element, the current input terminals of the second and fourth unidirectional current elements, and the current output terminals of the second and fourth switches are directly connected by a second node,

the current output terminal of the first switch is directly connected to the current output terminal of the second unidirectional current element by a third node,

the current output terminal of the third switch is directly connected to the current output terminal of the fourth unidirectional current element by a fourth node,

the current input terminal of the second switch is directly connected to the current input terminal of the first unidirectional current element by a fifth node,

the current input terminal of the fourth switch is directly connected to the current input terminal of the third unidirectional current element by a sixth node,

when: (1) a single-phase alternating current supply is interconnected with the power converter through a full-wave bridge rectifier whose negative voltage terminal is directly connected to the second node, (2) the first motor winding has a first terminal directly connected to the positive terminal of the full-wave bridge rectifier and a second terminal directly connected to the fifth node, (3) the third motor winding has a first terminal directly connected to the positive terminal of the full-wave bridge rectifier and a second terminal directly connected to the sixth node, (4) the second motor winding has a first terminal directly connected to the third node and a second terminal directly connected to the fifth node, and (5) the fourth motor winding has a first terminal directly connected to the fourth node and a second terminal directly connected to the sixth node, then:

a first operational mode exists in which current is conducted through the first motor winding, while the second switch is activated,

a second operational mode exists in which current is conducted through the third motor winding, while the fourth switch is activated,

a third operational mode exists in which current is conducted through the first motor winding and the first unidirectional current element to the capacitive element to charge the capacitive element, while the second switch is deactivated,

a fourth operational mode exists in which current is conducted through the third motor winding and the third unidirectional current element to the capacitive element to charge the capacitive element, while the fourth switch is deactivated,

a fifth operational mode exists in which energy stored by the capacitive element during the third or fourth operational modes is discharged by the conduction of current through the second motor phase winding when both the first and second switches are activated, and

a sixth operational mode exists in which energy stored by the capacitive element during the third or fourth operational modes is discharged by the conduction of current through the fourth motor phase winding when both the third and fourth switches are activated.

11. A power converter for supplying power to first and second series-connected windings of a first motor phase and third and fourth series-connected windings of a second motor phase, the power converter comprising:

first, second, and third unidirectional current elements that each conducts current in only one direction between a current input terminal and a current output terminal;

a capacitive element for storing energy across first and second terminals;

first, second, and third switches that each conducts current between a current input terminal and a current output terminal when activated and does not conduct current between the current input and output terminals when deactivated, wherein:

the first terminal of the capacitive element, the current output terminals of the first and third unidirectional current elements, and the current input terminals of the first switch are directly connected by a first node,

the second terminal of the capacitive element, the current input terminal of the second unidirectional current element, and the current output terminals of the second and third switches are directly connected by a second node,

the current output terminal of the first switch is directly connected to the current output terminal of the second unidirectional current element by a third node,

the current input terminal of the second switch is directly connected to the current input terminal of the first unidirectional current element by a fourth node,

the current input terminal of the third switch is directly connected to the current input terminal of the third unidirectional current element by a fifth node,

when: (1) a single-phase alternating current supply is interconnected with the power converter through a full-wave bridge rectifier whose negative voltage terminal is directly connected to the second node, (2) the first motor winding has a first terminal directly connected to the positive terminal of the full-wave bridge rectifier and a second terminal directly connected to the fourth node, (3) the third motor winding has a first terminal directly connected to the positive terminal of the full-wave bridge rectifier and a second terminal directly connected to the fifth node, (4) the second motor winding has a first terminal directly connected to the third node and a second terminal directly connected to the fourth node, and (5) the fourth motor winding has a first terminal directly connected to the third node and a second terminal directly connected to the fifth node, then:

a first operational mode exists in which current is conducted through the first motor winding, while the second switch is activated,

a second operational mode exists in which current is conducted through the third motor winding, while the fourth switch is activated,

a third operational mode exists in which current is conducted through the first motor winding and the first unidirectional current element to the capacitive element to charge the capacitive element, while the second switch is deactivated,

a fourth operational mode exists in which current is conducted through the third motor winding and the third unidirectional current element to the capacitive element to charge the capacitive element, while the third switch is deactivated,

a fifth operational mode exists in which energy stored by the capacitive element during the third or fourth operational modes is discharged by the conduction of current through the second motor phase winding when both the first and second switches are activated, and

a sixth operational mode exists in which energy stored by the capacitive element during the third or fourth operational modes is discharged by the conduction of current through the fourth motor phase winding when both the first and third switches are activated.

12. A power converter for supplying power to first and second windings of a motor phase, the power converter comprising:

a unidirectional current element that conducts current in only one direction between a current input terminal and a current output terminal;

a capacitive element for storing energy across first and second terminals;

a switch that conducts current between a current input terminal and a current output terminal when activated and does not conduct current between the current input and output terminals when deactivated, wherein:

the first terminal of the capacitive element is directly connected to the current output terminal of the unidirectional current element by a first node,

the current input terminal of the unidirectional current element is directly connected to the current input terminal of the switch by a second node,

when: (1) a single-phase alternating current supply is interconnected with the power converter through a full-wave bridge rectifier whose negative voltage terminal is directly connected to the current output terminal of the switch and whose positive terminal is directly connected to the second terminal of the capacitive element by a third node, (2) the first motor phase winding has a first terminal directly connected to the third node and a second terminal directly connected to the second node, and (3) the second motor phase winding has a first terminal directly connected to the first node and a second terminal directly connected to the third node, then:

a first operational mode exists in which current flows through the first motor phase winding, while the first switch is activated,

a second operational mode exists in which energy stored in the first motor phase winding is discharged by the conduction of current through the unidirectional current element into the capacitive element, to be stored as energy, and the second motor phase winding when the first switch is deactivated, and

a third operational mode exists in which energy stored in the capacitive element during the second operational mode is discharged by the conduction of current through the second motor phase winding, while the switch is activated or deactivated.

13. A stator for a motor, the stator comprising:

multiple stator poles that each has a coil winding around it to induce a flux through the pole when an electrical current flows through the winding and a rotor is aligned to circulate the flux; and

a first coil winding around the back iron of the stator that is disposed at a location of the back iron that does not experience flux reversal due to the excitation of the coil windings around the stator poles; and

a second coil winding around the back iron of the stator that is disposed at another location around the back iron that does not experience flux reversal due to the excitation of the coil windings around the stator poles, wherein:

the two coil windings around the back iron generate flux in opposite directions through the back iron when excited to generate a flux, and

the first coil winding around the back iron produces flux in the same direction through the back iron as do the coil windings around two of the stator poles, when each of the coil windings is excited to generate a flux.

14. The stator of claim 13, wherein each of the two coils around the back iron are disposed at corners of the back iron.

15. The stator of claim 14, wherein the two coils are disposed at opposite corners of the back iron.

16. The stator of claim 13, further comprising salient portions of the back iron that partially enclose the side edges of the back iron windings so as to inhibit the back iron windings from sliding along the back iron between stator poles.

17. The stator of claim 16, wherein the salient portions are disposed on the inner face of the back iron.

18. The stator of claim 16, wherein the salient portions are disposed on the outer face of the back iron.

19. The stator of claim 15 wherein the number of stator poles is four.

20. A method of calculating a duty cycle command of a motor phase having two series-connected coil windings, the method comprising:

calculating, with a processor, the duty cycle command by using the equation:

$$T_e^*(t+T) = \frac{1}{2} \left(\frac{dL_{A_1}(\theta, i)}{d\theta} \right) \left[\frac{T \cdot V_m \sin(\omega t) - (1-d^*)V_{S1}}{L_{A_1}(\theta, i)} + i_1(t) \right]^2 + \frac{1}{2} \left(\frac{dL_{A_2}(\theta, i)}{d\theta} \right) \left[\frac{d^* T \cdot V_{S1}}{L_{A_2}(\theta, i)} + i_2(t) \right]^2$$

and known values of $T_e^*(t+T)$, $\frac{dL_{A_1}(\theta, i)}{d\theta}$, $\frac{dL_{A_2}(\theta, i)}{d\theta}$, T , V_m , ω , t , V_{S1} , $i_1(t)$, $L_{A1}(\theta, i)$,

$L_{A2}(\theta, i)$, and $i_2(t)$, where:

t is an initial time,

T is a period of time subsequent to time t ,

$T_e^*(t+T)$ is reference torque at time $(t+T)$,

θ is a position of a rotor of the motor,

$L_{A1}(\theta, i)$ is the inductance of a motor coil A_1 at rotor position θ for a fixed current i ,

$L_{A2}(\theta, i)$ is the inductance of a motor coil A_2 at rotor position θ for a fixed current i ,

ω is the speed of the rotor,

V_m is the peak voltage of an alternating current supply,

$i_1(t)$ is the inductance slope with respect to rotor position for a first coil winding of the motor phase,

$i_2(t)$ is the inductance slope with respect to rotor position for a second coil winding of the motor phase, and

V_{s1} is the voltage applied across the second coil winding of the motor phase, monitoring the values of $i_1(t)$ and $i_2(t)$ after a period of time T ; and recalculating the duty cycle command.

21. A method of generating a signal to control energization of a motor phase, the method comprising:

generating a current command from a torque command;

generating an equivalent sine reference by multiplying the generated current command by an attenuated rectified signal obtained from a supply alternating current (ac) voltage;

generating the signal to control energization of the motor phase by multiplying the generated equivalent sine reference by a phase enabling signal for the motor phase.

22. A method of generating a duty cycle command of a motor phase, the method comprising:

generating a normalized conduction pulse based on a signal for energizing the motor phase and the dwell angle of the motor phase;

generating, with a processor, a current command by multiplying the generated conduction pulse by a current command for the motor phase;

generating a phase current error by subtracting an indicator of the current within the motor phase; and

generating the duty cycle command from the generated phase current error.

23. A method of generating a duty cycle command of a motor phase, the method comprising:

estimating, with a processor, phase air gap power from current and voltage applied to each of two series-connected coil windings of the motor phase;

generating a speed error of a rotor of the motor by subtracting the rotor's actual speed from its reference speed;

generating a torque command from the generated speed error;

generating an air gap power command by multiplying the generated torque command by the rotor's reference speed;

generating an air gap error by subtracting the estimated air gap power from the generated air gap power command; and

generating the duty cycle command from the air gap error.

24. A method of generating a duty cycle command of a motor phase, the method comprising:

calculating, with a processor, air gap power for the motor phase from current and voltage applied to each of two series-connected coil windings of the motor phase;

generating a speed error of a rotor of the motor by subtracting the rotor's actual speed from its reference speed;

generating a torque command from the generated speed error;

generating an air gap power command by multiplying the generated torque command by the rotor's reference speed;

generating stator resistive losses from the generated torque command;

generating an air gap error by subtracting the estimated air gap power from the sum of the generated air gap power command and the generated stator resistive losses; and

generating the duty cycle command from the air gap error.

25. A method of generating a duty cycle command of a two-phase motor comprising two series-connected coil windings for each of the two phases, the method comprising:

generating a first torque error for a first of the two windings of a first of the two motor phases based on the current applied to the first winding of the first phase and the position of a rotor of the motor;

generating a second torque error for a second of the two windings of the first motor phase based on the current applied to the second winding of the first phase and the rotor position;

generating a third torque error for a first of the two windings of a second of the two motor phases based on the current applied to the first winding of the second phase and the rotor position;

generating a fourth torque error for a second of the two windings of the second motor phase based on the current applied to the second winding of the second phase and the rotor position;

generating, with a processor, a fifth torque error by adding the first, second, third, and fourth torque errors; and

generating the duty cycle command from the fifth torque error and a torque error command.